Supporting decision making under uncertainty: Development of a participatory integrated model for water management in the middle Guadiana river basin

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A B S T R A C T

Following the Integrated Water Resources Management approach, the European Water Framework Directive demands Member States to develop water management plans at the catchment level. Those plans have to integrate the different interests and must be developed with stakeholder participation. To face these requirements, managers need tools to assess the impacts of possible management alternatives on natural and socio-economic systems. These tools should ideally be able to address the complexity and uncertainties of the water system, while serving as a platform for stakeholder participation. The objective of our research was to develop a participatory integrated assessment model, based on the combination of a crop model, an economic model and a participatory Bayesian network, with an application in the middle Guadiana sub-basin, in Spain. The methodology is intended to capture the complexity of water management problems, incorporating the relevant sectors, as well as the relevant scales involved in water management decision making. The integrated model has allowed us testing different management, market and climate change scenarios and assessing the impacts of such scenarios on the natural system (crops), on the socio-economic system (farms) and on the environment (water resources). Finally, this integrated assessment modelling process has allowed stakeholder participation, complying with the main requirements of current European water laws.

Keywords:
Integrated assessment modelling
Water management
Bayesian networks
Economic model
Crop model
Participatory modelling

1. Introduction

Water management problems are expected to increase as a consequence of climate change. This will enhance current water pressures, requiring an adaptation of management strategies (Ludwig et al., 2009). The need to adopt new approaches to water management is particularly acute in areas such as the European Mediterranean region, where water scarcity is attaining critical levels (Sagardoy and Varela-Ortega, 2010). In line with many other government policies worldwide, the European Water Framework Directive (WFD) (European Commission, 2000) has adopted the Integrated Water Resources Management approach (IWRM). This has been defined by the Global Water Partnership as "a co-ordinated development and management of water, land and related resources, which would allow the maximisation of economic and social welfare in an equitable manner while assuring the sustainability of vital ecosystems" (GWP, 2000). The Directive requires member states to develop integrated management plans at the catchment level. In the implementation of plans Members are required to encourage public participation, to adopt the precautionary principle, and to follow the principles of subsidiarity and transparency (Rault and Jeffrey, 2008).

Embedded in the IWRM philosophy, but more specifically related to decision making support, is the concept of Integrated Assessment Modelling (IAM), defined by Rotmans and Van Asselt (1996) as "an interdisciplinary and participatory process combining, interpreting and communicating knowledge from diverse scientific disciplines to allow a better understanding of complex phenomena". Compared to more traditional modelling approaches, IAM is characterised by the use of integrated frameworks in which scientists, stakeholders

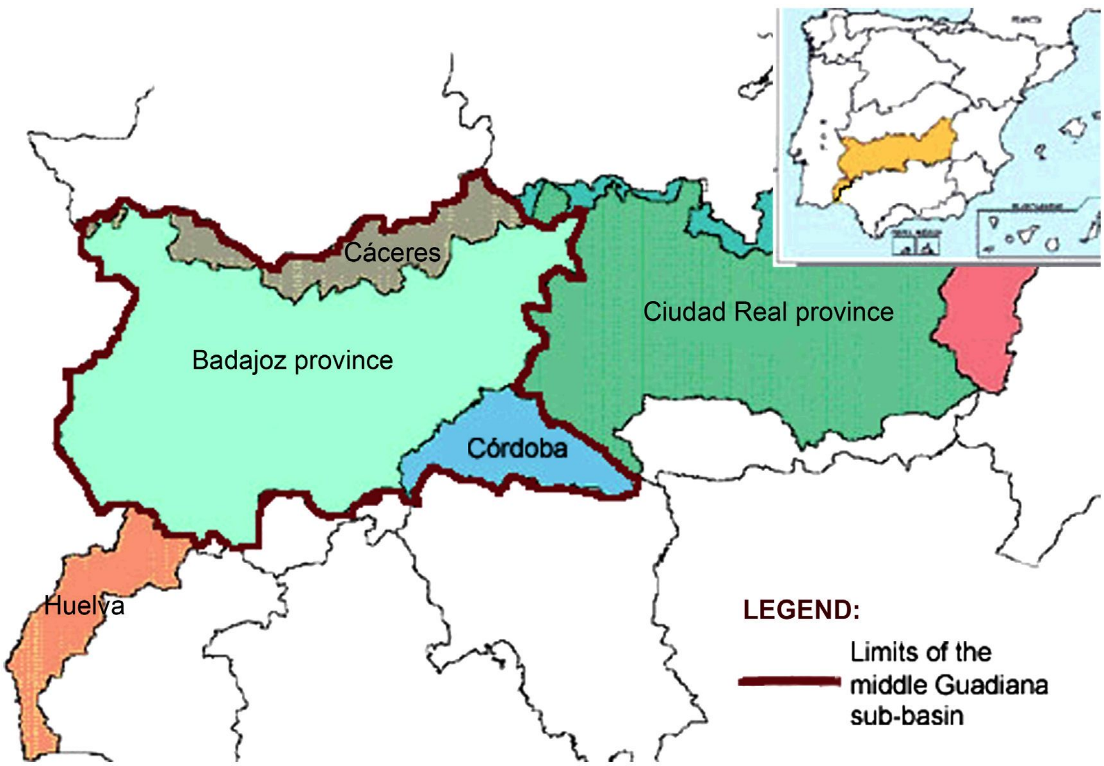

Fig. 1. Spanish part of the Guadiana river basin: location and regions.

and decision makers are involved in an iterative communication process (Rotmans and Van Asselt, 1996; Van Ittersum et al., 2008).

Many researchers have stressed the benefits of integrated modelling to address complexity and uncertainty of environmental systems; such models are able to capture the interactions between human and natural systems (Jakeman and Letcher, 2003; Kelly et al., 2013; Kragt et al., 2013; Liu et al., 2008). But the effectiveness of models is considerably improved if stakeholders can be closely involved in the modelling process (Korfmacher, 2001; Prell et al., 2007; Voinov and Bousquet, 2010). This is because participation provides the means to foster communication, encourage social learning and to improve understanding of the system by including local knowledge which may not be available to the modellers. Furthermore effective participation can contribute to a sense of ownership of the decision process and to more chance that the policy is ultimately accepted (Lamers et al., 2010; Rowe and Frewer, 2000; Zorrilla et al., 2009).

In the past it has been difficult to combine the involvement of stakeholders with the construction of integrated assessment models (Antunes et al., 2009; Orr et al., 2007; Rivington et al., 2007; Van Delden et al., 2007). Both the stakeholder involvement and the integrated assessment modelling offer considerable advantages but far better results could be obtained if the two approaches could be combined (Hisschemöller et al., 2001).

The objective of this study was the development of a methodological framework to support decision making in water management under uncertain conditions, capable of supporting the simulation of future scenarios and to capture the different scales relevant to water use. To that end, a participatory integrated modelling framework was developed and applied in a river basin in Spain. This methodology was intended to represent: the plot and the way crops respond to the environment; the decisions of the farmers faced with policy and environmental constraints; and the decisions taken by water managers at the regional scale.

The modelling exercise is intended to address the requirements of the WFD to integrate different disciplines and participation of interested parties. The study area is the middle Guadiana sub-basin, in Spain, an area where water management has important social and environmental implications. The integrated model should be able to account for the trade-offs between those two aspects. Simulations were carried out to assess the impacts of possible future scenarios and management options on the socio-economic system and on the environment. The whole process was supported in the collaboration between experts and stakeholders, as a means to address the complexity of human-environmental systems (Magnuszewski et al., 2005).

2. Case study overview: the middle Guadiana basin, in Spain

This research was developed in the central parts of the Guadiana basin in central Spain. The basin covers 67,148 km^2, of which the middle Guadiana has an area of 26,194 km^2; Fig. 1 shows the location of the middle Guadiana sub-basin.

One of the main characteristics of the Guadiana basin is that it is highly regulated, with a storage capacity of 9439 Mm^3 in the Spanish part, mostly located in the middle Guadiana. The climate is continental Mediterranean, with highly variable temperatures, an average precipitation of 590 mm and an annual evaporation of 800–1000 mm, resulting in a high aridity index. This, together with variable precipitation throughout the year, means that irrigation is essential to maintain a high level of agricultural activity and economic stability in the area. This is especially important since the agricultural sector accounts for 57% employment in the area and a decreasing population which is only maintained in those municipalities which have an important development of irrigation (Confederación Hidrográfica del Guadiana, 2010).

The middle Guadiana has 145,258 ha of irrigated land, most of it (83.5%) satisfied with surface water. As a result of an extensive

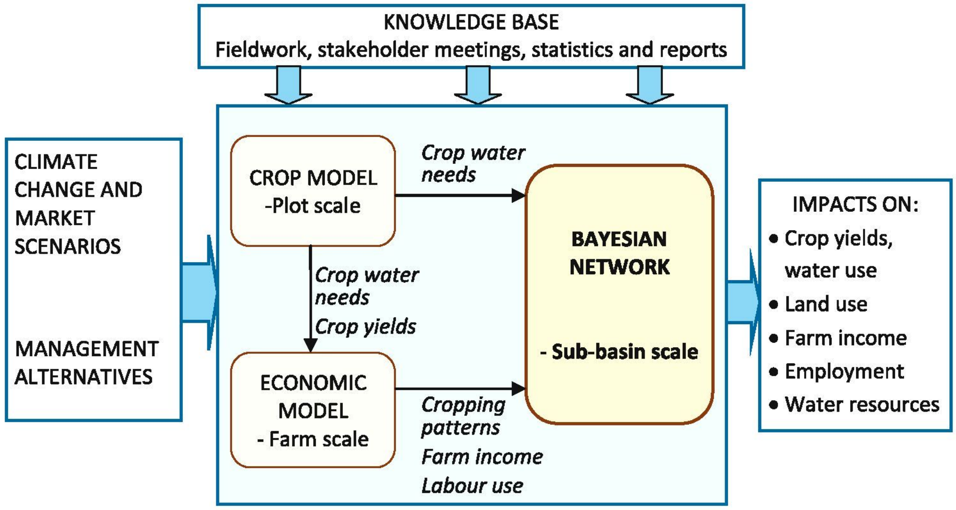

Fig. 2. Integrated modelling framework developed in the middle Guadiana basin study.

agriculture-based rural development programme (Baigorri-Agoiz, 1997; Gómez-Pompa, 2002), a major shift from rain fed to irrigated agriculture was produced over a considerable surface, accompanied by the construction of a big number of dams. Irrigation exhibits, in turn, a lower efficiency of water use and a lower water productivity than other parts of the basin, increased modernisation of irrigation systems being one of the challenges in the area.

An integrated management plan to deliver water of acceptable quality is required by the WFD for the Guadiana basin by 2015 (EC, 2000). This requirement demands the development of appropriate tools to allow the exploration of scenarios and management options to assess the impacts of possible alternatives on the regional economy and the environment. This is particularly relevant in this area, where irrigation is the main pillar of socio-economic development. Any decision or scenario affecting water resources can have important implications on the economy of the region and on the attainment of the environmental standards aimed by the WFD, especially in the respect of the environmental flows. With this research, we intended to develop an appropriate methodological approach for the middle Guadiana context, based on previous studies carried out in the upper Guadiana (Carmona et al., 2011a, 2011b) but adding new elements which can capture the crop behaviour and allow the consideration of climate change within the simulation scenarios.

3. Participatory development of an integrated modelling framework

The methodology applied in this study aimed at the development of an integrated model to be used for decision support in water management. The model includes three elements: (1) a crop model which represents the crops functioning, (2) an economic mathematical programming model which reproduces the strategies followed by farmers in the area, and (3) a Bayesian network (BN) built at the sub-basin scale which simulates the whole system. The methodological scheme provides the framework for effective stakeholder participation which takes place at different stages of the modelling process and in the definition of the simulation scenarios. Compared to previous studies developed in other parts of the Guadiana basin (Carmona et al., 2011b), the present research adds a crop model in order to study the vulnerability of the agricultural systems. That new framework allows linking the different scales of analysis which are relevant for water use, from paddock to catchment scales. The components of the integrated modelling framework and the connections between them are shown in Fig. 2.

BNs were used as a metamodel, gathering information from the other two models, as in Kragt et al. (2011) and Barton et al. (2008) and, at the same time, were used as a vehicle for participation (Bromley et al., 2005; Henriksen et al., 2007).

The three models were designed and developed in a synchronised way to ensure the transferability of data between them, as described in Kragt et al. (2011). They were also designed with the same annual time frame in order to obtain coherent results.

Although the three models were built in parallel and all three benefited from stakeholder input, only the BN was really designed in a participatory way in the form of a series of meetings at which stakeholders contributed at all stages, from the problem definition to the validation of the model. In this paper, we focus on the development of the participatory integrated model rather than the participatory process (that is, the analysis of conflicts, social learning process, etc.), which is discussed in Carmona et al. (2013).

3.1. *Fieldwork and database*

An extensive database was created using information obtained from the field, field experiments provided by experimental farm, scientific reports, literature searches and stakeholder meetings carried out within the context of the SCENES (http://goo.gl/EX3JB) and MEDIATION (http://www.mediation-project.eu/) projects. The data types include information on the water users in the area, the type of agriculture, agronomic data (crops, yields and cropping techniques), economic data (structure of the farms, costs and income), the nature of water management at the river basin and at the irrigation community (IC) level (the level at which many water management decisions are taken), social data, and information about environmental issues.

The next step was, based on the information collected, to define representative farms which would represent the irrigated farms in the sub-basin in terms of cropping patterns, water use, technology, etc. First, four irrigation communities were selected (from a total of 20), accounting for most of the irrigated agriculture in the region (64.4% of total surface and 71.1% of farms in the sub-basin): (1) *Montijo*: old IC with a high percentage of surface irrigation; (2) *Orellana*: old IC, with surface irrigation and a high proportion of

Table 1
Representative farms selected for the middle Guadiana sub-basin.

REPRESENTATIVE FARMS	SURFACE (ha)	CROPPING PATTERN		
F1-Montijo	12	*Tomato*	*Maize*	
F2-Orellana	20	*Rice*	*Maize*	
F3-Zújar	30	*Tomato*	*Maize*	*Olive tree*
F4-TDirectas	100	*Tomato*	*Peach tree*	

rice, the most water consuming crop in the sub-basin; (3) *Zújar*: modern IC with highly efficient pressurised irrigation systems; and (4) *Tomas Directas*: modern IC with pressurised irrigation systems and water uptake directly from the river.

Based on the results from 162 farm surveys, one representative farm was defined for each of the selected irrigation communities (Table 1).

Following the definition of the farm typology, the crop simulation models, the farm economic models and the Bayesian networks were developed.

3.2. *The agricultural component: a crop simulation model*

AquaCrop is a recently released crop model, developed by the Land and Water Division of the FAO, which reproduces crop response to water (Hsiao et al., 2009; Raes et al., 2009; Steduto et al., 2009). The model is especially suited for situations in which water is a limiting factor and allows the crop response to different water stress situations to be tested (García-Vila and Fereres, 2012; Steduto et al., 2009), and it has also been used to simulate climate change (Vanuytrecht et al., 2011).

Unlike other crop simulation models, AquaCrop uses an exclusively water-driven growth module, which means that the driver for growth and biomass production is the consumptive water use. This entails lower input data requirements than other well established models, such as CROPSYST (Stöckle et al., 2003), which has water and radiation driven growth modules, or WOFOST (Van Diepen et al., 1989), with growth modules driven by carbon and radiation. AquaCrop has given results similar to other models when it was tested for different water regimes (Todorovic et al., 2009).

AquaCrop has several interrelated sub-components: crop (including crop development, growth and yield), soil (water balance), atmosphere (temperature regime, rainfall, evaporative demand, CO_2 concentration) and management (agronomic practices, such as irrigation). Fig. 3 shows how those sub-components are linked.

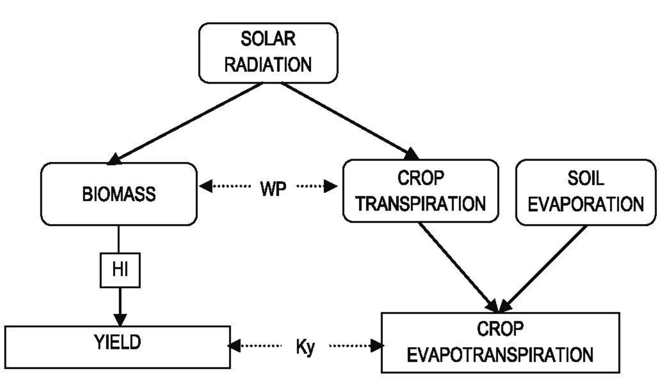

Fig. 3. Scheme of AquaCrop calculations.
Source: adapted from Steduto et al. (2008)

Calculations are made on a daily basis, and are based on the fundamental relation of the yield estimate in response to water availability, published by Doorenbos and Kassam (1979), where biomass is calculated as a function of water productivity (WP) and transpiration (Tr). Water stress is simulated by introducing stress coefficients applied to the growth functions.

AquaCrop has been used in the central Guadiana to model some of the most representative irrigated crops in the area: wheat, barley, maize, sunflower, rice, tomato, potato, broccoli, olive tree, peach tree and plum tree. However, other crops could not be modelled due to the lack of available data and to the difficulties of dynamic simulation models in handling with perennial crops.

We obtained field experiment data for: wheat, barley, sunflower, maize and tomato. For the other crops, we adopted the following approaches: for potato, we used a potato file calibrated for the upper Guadiana and for rice we used the default file. Calibration for these two crops was carried out using the crop data from the farm surveys and interviews. All field experiments provide non-limited irrigation; consequently calibration is carried out using an automatic irrigation schedule.

Climatic data – such as maximum and minimum temperature (T_{max}, T_{min}) and precipitation (P) – were obtained from two local weather stations. Reference evapotranspiration (ETo) was calculated following the FAO the Penman–Monteith approach, with the ETo calculator software (http://www.fao.org/nr/water/eto.html). Information on soils came from profiles in the "Catálogo de suelos de Extremadura" (http://www.unex.es/edafo/IndComarcas.html), and La Orden experimental field in the Guadajira municipality (http://www.centrodeinvestigacionlaorden.es). The various crops modelled in AquaCrop were calibrated using the default crop files supplied with the model, while climate and soil files were created using field data to proceed to local calibration. Apart from the management data (sowing date, sowing dose, irrigation, etc), the two main parameters used for calibration were the water productivity index (WP) and the harvest index (HI), which can vary within a certain range for a specific crop depending on the variety, climate and soil fertility.

3.3. *The social component: an economic farm simulation model*

The economic model that has been developed is a non-linear, constraint optimisation mathematical programming model. It is static (it considers one year), built at farm level and written in the General Algebraic Modelling System (GAMS) (http://www.gams.com).

The model allows the economic impacts of farm management decisions to be simulated. The theory behind this type of model assumes that farmers are rational decision makers (Von Neumann and Morgenstern, 1994). We consider that farm decisions are subject to risk and uncertainties, mainly due to natural hazards and market fluctuations (Ellis, 1993), which causes farm income to fluctuate from year to year. The farmer selects the activities which maximise a utility function, subject to surface, labour and water constraints (see Carmona et al. (2011a,b) for a similar model).

The utility function has been defined by taking the mean–standard deviation approach (Hazell and Norton, 1986): the farmer's utility (U) is defined as the expected gross margin (Z) minus the standard deviation of gross margin ($\sigma(Z)$) affected by a risk aversion coefficient (φ):

$$U = Z - \varphi \cdot \sigma(Z)$$

The gross margin is determined by yields, prices, subsidies and other variable costs. This gross margin is affected by its standard deviation and by a risk aversion coefficient which represents the extent to which the farmer is willing to renounce a certain level of income to avoid risk. The value of the risk aversion coefficient has been the parameter used for calibration.

Technical coefficients of the model (yields, variable costs, prices, subsidies, water needs, labour requirements…) have been obtained from fieldwork, from a local agricultural consultancy firm (TEPRO, www.tepro.es), and from different official statistics and reports.

Economic mathematical programming models have commonly been used in combination with agronomic (García-Vila and Fereres, 2012; Louhichi et al., 2010) or hydrologic models (Varela-Ortega et al., 2011) in an integrated framework to assess the impact of policy and climate scenarios.

Although other time frames could have been chosen for the economic model, we opted for an annual step for several reasons: 1) the economic results of most interest (farm income) are best calculated on an annual basis, 2) one of the main controlling factors, water allotments, are assigned annually, 3) the main results of the economic model provided input to the BN, and this also has an annual time frame. The use of the same time scale for the models used in an integrated framework is required to facilitate the interchange of information and to obtain coherent results of scenario simulations (Kragt et al., 2011).

3.4. *The regional scale BN*

The third component of the modelling framework was a BN which represented the whole sub-basin. Like any other modelling exercise, the construction of a BN demands a thorough understanding of the variables involved in the system and the causal links between them. But some of the specific features of a BN that make it an increasingly popular tool to model complex and uncertain domains, such as environmental problems, are (Chan et al., 2010; Chen and Pollino, 2012; Uusitalo, 2007): (a) their capacity to combine variables from different disciplines and data from different nature, (b) their explicit consideration of uncertainty, which is expressed through probability, (c) their ability to handle with missing data, and (d) the potential to combine them with other types of models or analytic tools. Moreover, their graphical representation makes them easy to understand and to be particularly useful as an aid to the participatory process (Bromley et al., 2005; Henriksen et al., 2007).

BNs are probabilistic models composed of a set of variables connected through causal links, forming a directed acyclic graph. Each variable A has a set of possible states, which are mutually exclusive. When a variable A depends on other variables B, C, etc., a conditional probability table has to be specified showing the probabilities of A adopting a certain state as a function of the states of its parents B, C, etc. When we build a certain BN, it has a unique joint probability distribution and, thanks to this property, the model can calculate the probabilities of any variable in the BN when new evidence is provided for any other variable in the BN. Among the available software packages to represent and solve BNs, we have used Hugin (http://www.hugin.com).

In our research, the BN is used to represent the whole catchment system and to integrate the knowledge obtained from the economic and the crop models. This can be done thanks to the ability of BNs to combine different types of data (Borsuk et al., 2004; Chan et al., 2010; Uusitalo, 2007).

In our case, BNs have been constructed with the stakeholders, who have participated from the very first step in the process as recommended in the guidelines of Bromley (2005). The process included five meetings (plenary meetings or group interviews), held between May 2008 and February 2011, covering all stages in the BN development: from a preparatory meeting to an evaluation meeting. Between meetings, researchers worked in the rearrangement of some variables and links that were inconsistent, and also in the data gathering, which required considerable time and effort. Changes in the structure, data sources and datasets were always discussed with stakeholders, who gave their critical opinions and throughout the entire process helped guide the researchers to collect whatever local information was available. At the final meeting the results of the BN along with those from the economic and the crop models were presented and discussed. Stakeholder input at this stage helped with the validation of the models.

The information to define the states of the variables and the probability distributions has been taken from the best available data source in each case, as recommended by Bromley (2005). For some variables the results from the economic and crop models were used as input; for other variables statistical data, scientific reports, and expert or stakeholder opinions were used for input data. Based on the based available data, the probability distributions were created following expert judgement and then validated with stakeholders.

The participatory modelling process ultimately yielded a unique BN for the whole sub-basin. To reach this point a sub-network was developed for each of the 4 farm types to produce four separate networks. These farm-specific sub-networks have the same structure, but differ in the values of the CPTs. The existence of repetitive structures within a BN can be exploited during the construction of the model by building a unique structure and to *instantiate* it as many times as required. The result is an object-oriented BN (Bangsø and Wuillemin, 2000; Carmona et al., 2011a; Koller and Pfeffer, 1997; Molina et al., 2010). We have used this approach to construct a unique model to represent the structure of a farm system. The final aggregated structure is formed of 6 sub-networks: one "inputs" network including climate, market and management variables, four sub-networks corresponding to each one of the farm types, each of them weighted according to their representativeness in the region, and one "general" sub-network comprising the variables applying to the whole system (see appendix). The introduction of new evidence in any of the system variables is transmitted to the whole complex, allowing the assessment of impacts that potential measures or scenarios could have on the different farm types and on the environment in one simulation run.

3.5. *Integrating model components into a common framework*

Within the described modelling framework, some of the results of simulations performed with one model are used as an input for other models. The sequence in the development of the modelling framework was: first, the crop simulation model, whose results are needed as an input for both the economic model and the BN; secondly, the economic model; and finally, the BN, which receives input from the other two models.

The crop model is linked to the economic model through the use of linear programming (LP) matrices, which contain the coefficients affecting the different variables in the model equations for every

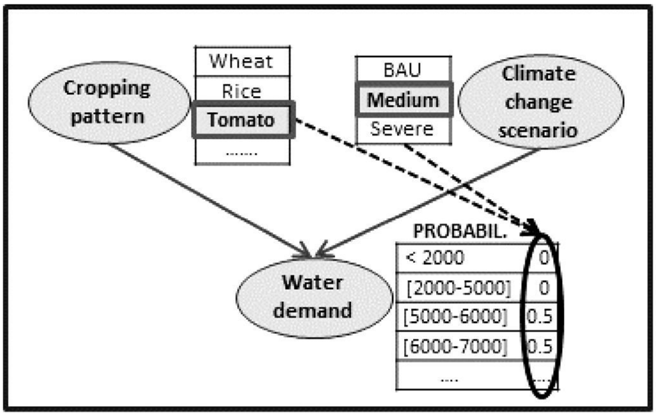

Fig. 4. Link between the AquaCrop model and the BN.

potential activity Xi, which represents a crop cultivated with a specific technique (see Pannell (1997) for more details on LP matrices). The data included in these matrices comes from the fieldwork, statistics and reports. For the climate change scenarios, where no historical data is available for yields or for crop water requirements, the coefficients for those two variables are obtained from the results of simulations with the crop model.

This way, the information obtained from the crop model can be used in the economic model to identify crop distributions selected by farmers under the new conditions corresponding to the future climate scenarios, and also to calculate the total water consumption and the farm income in those scenarios.

The BN receives input from both the AquaCrop model and the economic model. AquaCrop is used in the BN to provide water needs for various crops under different climatic scenarios. These data are used to populate the CPTs associated with the "water demand" node, relating water needs with crops and with climate change scenarios (see Fig. 4).

Similarly, the results of the economic model are also used to fill some other CPTs in the BN. For every farm type, we introduce the information concerning the following variables: cropping patterns (related to water availability and climate change scenarios), water use (related to climate change scenarios) and farm income (related to climate change and market scenarios).

3.6. Simulation scenarios

Finally, the integrated model was used to carry out simulations of several scenarios, which represent different options for: climate change, water allotments, on-farm modernisation, market (product and input) prices, control of cross compliance, regulation of subsidies for integrated production and improvement of conveyance losses. These groups of scenarios, which are explained below, were simulated by the different models, like shown in Fig. 5:

The explanation of these scenarios is given next:

A) Climate change scenarios
- *BAU*: corresponds to the current climate.
- *Severe*: corresponds to the A2 IPCC socio-economic scenario (IPCC, 2000), where CO_2 emissions result in a severe climate change.
- *Moderate*: corresponds to B1 IPCC socio-economic scenario, where reduced CO_2 emissions, following the adoption mitigation measures, end up in a moderate climate change.

Historical climatic data is taken from the Spanish Meteorological Agency (AEMET, 2009). For climate change scenarios, datasets were produced from historical data, using the stochastic weather generator LarsWG5 (Semenov and Doblas-Reyes, 2007; Semenov, 2008).

B) Management scenarios
- *Current water use*: data obtained from fieldwork (which can be over water allotment permits).
- *Legal allotments*: consumption constraint to current water allotments provided by the current river basin management plan (Confederación Hidrográfica del Guadiana, 1998).
- *Reduced 23%*: reduction of water allotments of 23% compared to current values, according to the decrease in water resources for the Guadiana river basin under a moderate climate change scenario (Ayala-Carcedo, 2001).
- *Reduced 33%*: reduction of water allotments of 33% compared to current values, according to the decrease in water resources for the Guadiana river basin under a severe climate change scenario (Ayala-Carcedo, 2001).

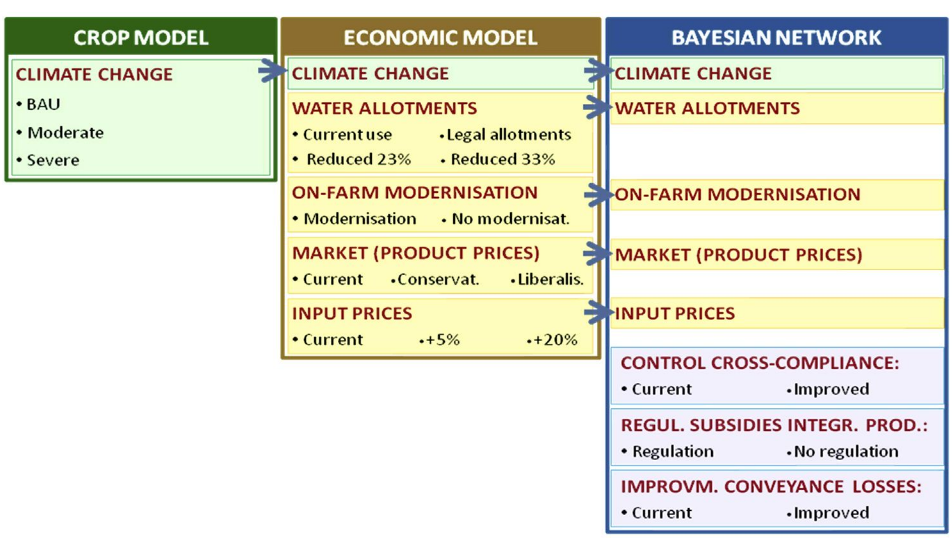

Fig. 5. Blocks of scenarios and their simulation in the different models.

C) On-farm modernisation
- *No modernisation*: current technology.
- *Modernisation*: only for farms with old irrigation systems (gravity), change to pressurised irrigation.

D) Market scenarios. Several combinations of input and product prices are considered:
- *Current*: corresponds to a 'business as usual' scenario.
- Changes in input prices: *+5%* and *+20%*, which correspond, respectively, to a moderate and a high increase of input prices within the variation ranges registered for the period 2001–2008 by the National Statistics Institute (INE: http://www.ine.es)
- Changes in product prices and subsidies: two scenarios are considered. The *conservative* one takes changes in prices forecasted by OCDE-FAO (OECD-FAO, 2010); the *liberalisation* scenario assumes a liberalisation in the future markets, leading to the price changes reported in Nowicki et al. (2007) and Nowicki et al. (2009). For changes in subsidies, we have taken indications given in Nowicki et al. (2007) and Nowicki et al. (2009).

E) Control of cross-compliance:
- *Current*: corresponds to the actual water consumption level.
- *Improved*: increased compliance with water allotments established by law, which can lead to a reduction of nitrate pollution and water consumption (Junta de Extremadura, http://goo.gl/ihzvR)

F) Regulation of subsidies for integrated production: *regulation* and *no regulation*. Stakeholders affirmed that an important volume of water could be saved if rice cultivation were restricted to a certain type of soils which are classified as suitable for rice, especially in Orellana IC. We have estimated 13% of Orellana IC surface.

G) Improvement of conveyance losses: it refers to modernisation in the distribution network, which can improve efficiency in distribution and transport from 0.71 (*current*) to 0.81 (*improved*) (Confederación Hidrográfica del Guadiana, 2010).

3.7. The essential role of stakeholders in the modelling process

The role played by stakeholders along the modelling process has been crucial in the development of all model components. This is an obvious remark in the case of the BNs, which have been co-built with them from the early stages of the BN design. But also the crop model and the economic model benefited from stakeholder interaction along the process. Participants in the BN development workshops were also asked questions related to the development of the two other models, and results of those models were shown in the meetings to get their feedback and validate the results. Fig. 6 illustrates that interaction.

The whole integrated modelling process was an iterative approach where the interested parties had always voice to add their inputs to the models. This served us researchers to better understand the problems and the system to be modelled, to acquire information and guideline about data sources, to contrast our models with the reality as perceived by stakeholders, and finally it allowed us to validate the models. Additionally, the participation of stakeholders also helped their comprehension and acceptance of the modelling tools and of the results obtained from simulations, presented in the next section.

4. Results

This section describes the results of simulations using the integrated model and then discusses the implications of these results.

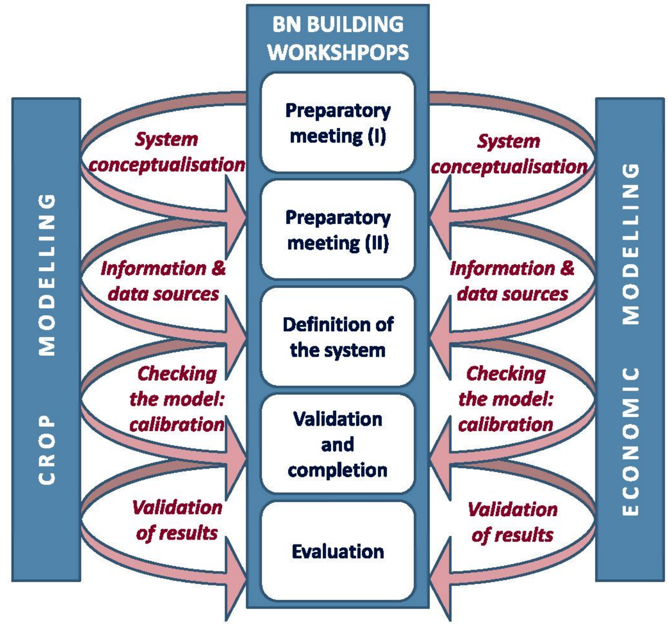

Fig. 6. Stakeholder contribution to the models: feedback loops along the modelling process.

4.1. Results of crop model simulations

As explained in Section 3.2, crop model simulations provide us with estimates of crop yields and water needs for the different climate change scenarios proposed. These results are shown in Figs. 7 and 8. Fig. 9 presents changes in crop water demands for 2080–2099, compared to current demands; Fig. 8 shows changes in yields for the same period.

According to the AquaCrop results, the climate change scenarios used would all result in an increase in crop water demand for most crops and an increase in yield. Some of the negative effects of climate change are partly compensated by the positive effects that an increase of CO_2 concentration can have on yields, due to its capacity to stimulate photosynthesis and to improve water use efficiency (Olesen and Bindi, 2002; Tubiello et al., 2007). We should point out that we are dealing with fully irrigated crops so that precipitation decrease does not have an impact on yield. For tree crops, yields and water use have been estimated from yield response to ET functions instead of using models. For this type of crops, one of the most often reported consequences of future climate scenarios are changes in phenology, such as flowering or ripening dates, which will necessarily have an impact on yields, although such an impact is difficult to estimate (Bindi et al., 1996; Lobell et al., 2006).

4.2. Results of the simulations with the economic model

If we look at the definition of scenarios explained in Section 3.6, we can see that there is a high number of possible combinations between the management–market–climate options, a small sample of which are shown here. Among the results, two kinds of outputs were crucial for the BN: the cropping patterns and the income. Fig. 9 shows the crop distribution in the sub-basin (aggregated through weighted summation of the different farm types) for some of the scenarios tested: (a) reference scenario, (b) compliance with the current water allotments established by law (PHN), (c) liberalisation and conservative market scenarios, and (d) the combination of the two climate change scenarios with the two

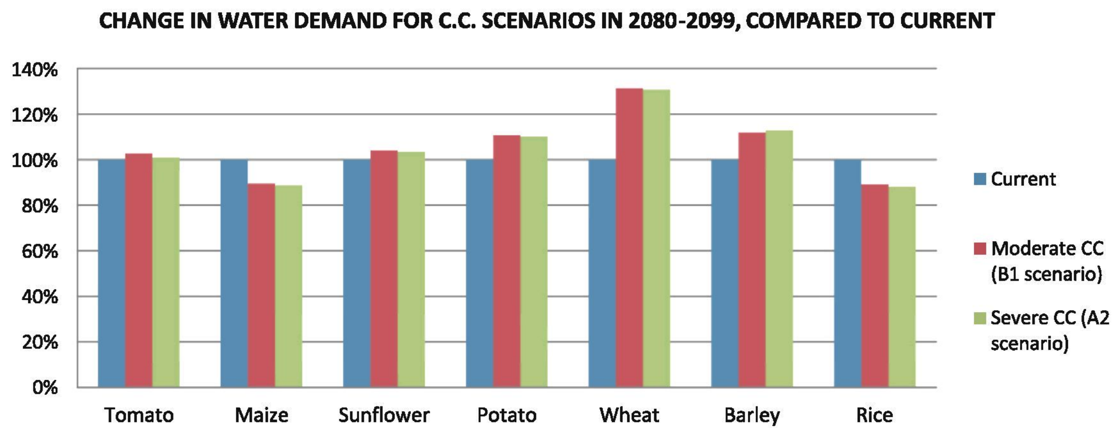

Fig. 7. Changes in water needs of the selected crops for the different climate scenarios (current, moderate and severe) in 2080–2099, given as percentage of change compared to current values.

imaginable future market scenarios. Fig. 10 shows the income obtained by every farm type for the same scenarios.

According to results shown in Fig. 9, improving farmers' compliance with water allotments currently established by law would limit future rice cultivation, which would instead be replaced by rain fed cereals and to a lesser extent by tomatoes. If we look at the market forces, a liberalisation scenario would, under current climate conditions, favour an increase in maize production. This crop would replace rice and to a certain extent tomato, while some rain fed cereal would compensate the increase in water demand. In turn, the conservative market scenario would lead to an increase in the production of rice in exchange for maize and some tomato. In this case, the increase of water demand would be compensated by the cultivation of sunflower, a low water demanding crop. Regarding the effects of climate change, potato and broccoli, two crops with lower water requirements and higher labour needs than the other options, would gain an important place in both market scenarios; water restrictions in a severe climate change scenario seem to minimise market influence in cropping decisions.

Results concerning farm income displayed in Fig. 10 highlight the differences in incomes obtained by the different farm types: (a) Tomas Directas IC, the largest type of farm with fruit trees and a highly efficient irrigation technology, obtains a much higher income for every scenario; (b) Zújar IC, which tends to smaller than type (a) but still has highly efficient irrigation systems, follows (a) in all scenarios; and (c) Montijo and Orellana IC, the smallest and least modern types with only annual crops, generally earn similar incomes, which are lower than for (a) and (b).

In terms of water use, an increase of compliance with current water restrictions would not cause a marked decrease on farm income for Tomas Directas and Zújar, because these two farm types are already showing a high compliance, while it would have a much higher impact in the older farms: a reduction of 18% for Montijo and 25% for Orellana, the IC with highest water consumption per surface unit due to a high proportion of rice. With respect to market conditions, conservative scenarios do not seem to have a negative impact on farm income, indeed in some cases it even leads to an increase. In contrast, a more liberal scenario has negative results for all farm types, with an income decrease of between 5 and 17%. Finally, regarding climate change scenarios, our results indicate that farm income could increase considerably in all representative farms and in both market scenarios considered, especially for the largest farms growing fruit trees. This might be due to yield increases having more impact on income, under climate change scenarios, than the effect of the cost of water use or the decrease in water availability.

4.3. Results of BN simulations

One interesting advantage of the object-oriented BN structure is that it has the information coming from the other models and

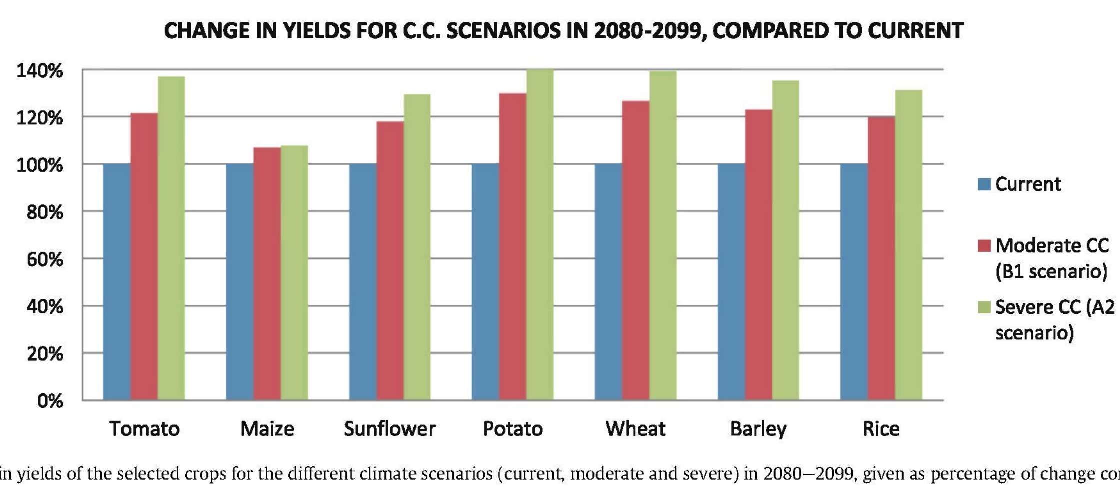

Fig. 8. Changes in yields of the selected crops for the different climate scenarios (current, moderate and severe) in 2080–2099, given as percentage of change compared to current values.

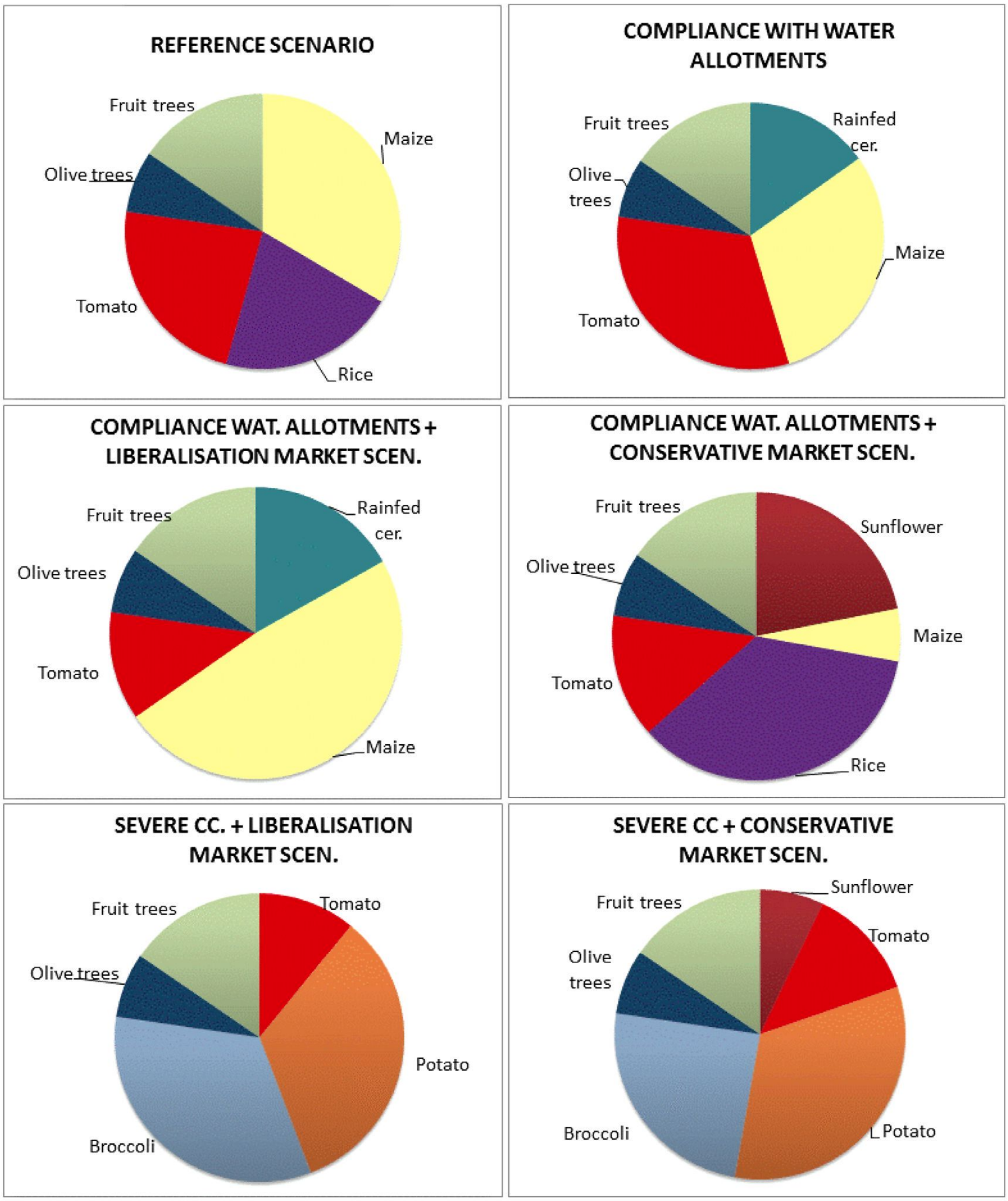

Fig. 9. Crop distribution in the middle Guadiana basin for some of the simulation scenarios (current climate for the four upper graphs, climate change scenario data relative to 2080–2099 in the last two graphs).

contains all the representative farms as part of the structure. Consequently, although the simulation results are aggregated at the regional level, we can also see results at the farm level, allowing a complete analysis at both scales. Some of the results of BN simulations are shown in Figs. 11–13. These show how different management, market and climate change scenarios affect the state of water resources, agricultural income and regional employment.

In order to assess the impacts of climate change scenarios, we have used the following regional indicators: respect of environmental flows, achievement of good status of water bodies and having sufficient water for irrigation. Fig. 11 shows results for the severe climate change scenarios. In this case, all three output variables – environmental restrictions, good status of water bodies and capacity to meet irrigation demands – are highly affected by the climate scenarios. The probability to obtain a good status for water bodies under severe climate change decreases by around 16% due to climate change, while the drop is 25% for the other two variables. These results are similar in both market scenarios, and they get even worse if water allotments for irrigation are reduced by 33%. Under climate change, the application of all input management measures together (management improvements, improved control of water consumption and cross compliance, and regulation of subsidies for integrated production) could increase between 9 and 15% the probabilities to attain the basin targets, compared to the situation without additional measures. Regarding the achievement of a good status of water bodies, its probability is

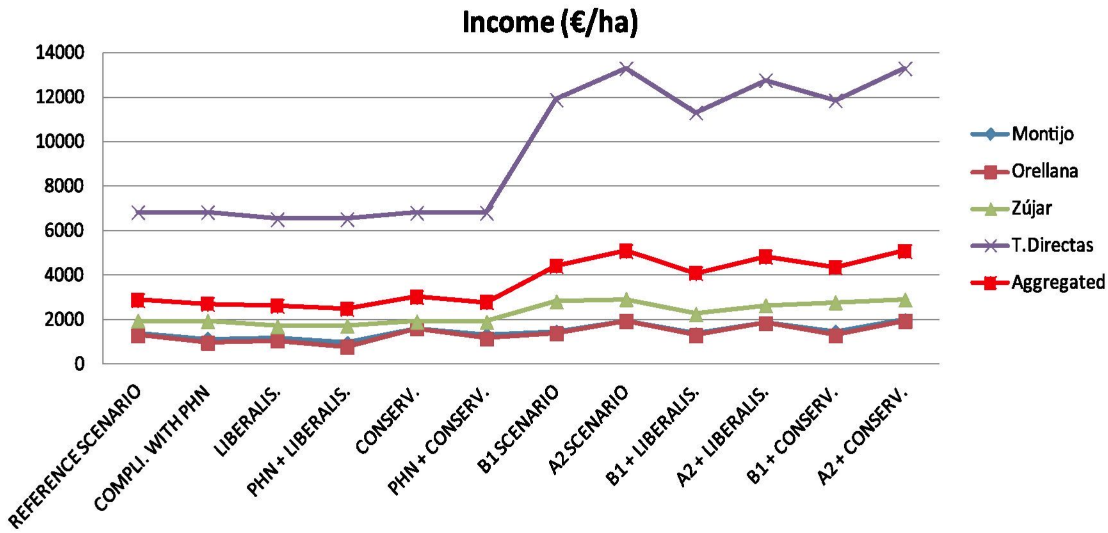

Fig. 10. Income for every farm type and aggregated results for some of the scenarios tested with the economic model: reference, compliance with water allotments, liberalisation and conservative market scenarios, and moderate and severe climate change combined with the two possible market scenarios.

lower than for the other basin objectives in all cases, and management measures simulated do not increase that probability to any great extent. This is due to the complex nature of this problem which is affected by other factors, such as point source pollution, which have not been included in the representation of the water system.

Fig. 12 shows the results of farm income for an average farm (weighted average of the four farm types) obtained from the simulations with the BN. In the horizontal axis, we have the different simulation scenarios, while the vertical axis represents the probability of the farm to attain given levels of income (ranges in colours (in online version)). While the results from the economic model (Fig. 10) provided us with farm incomes in an average year, the BN results show how those farm incomes are not assured, but there is a high range of possible economic outcomes. Considering these results, we can expect farmers to take production decisions not only aiming at the maximisation of income, but also at the reduction of the uncertainty.

Finally, Fig. 13 shows the way in which employment responds to the different scenarios. Like in the previous figure, results are given in terms of probability to attain a certain level of employment. Results show that the implementation of management measures directly aimed at reducing water use can produce an increase in employment. Similarly climate change scenarios also point to an important increase in agricultural employment. It seems that in water scarce scenarios, farmers' strategies of adaptation involve a shift from water intensive alternatives to other less water intensive and more labour intensive options. Water and labour are used as interchangeable input factors in the attempt to balance farm income. Compared to the income results, we can see that the probability distribution of the employment is more stable along scenarios. Although these probabilities change in the different scenarios, the change is not as important as for the income results.

5. Discussion

There is some published information relating to the use of BNs for integrated assessment (Borsuk et al., 2004; Croke et al., 2007; Ticehurst et al., 2007), but either they have not been built with the collaboration of stakeholders or have not been used in

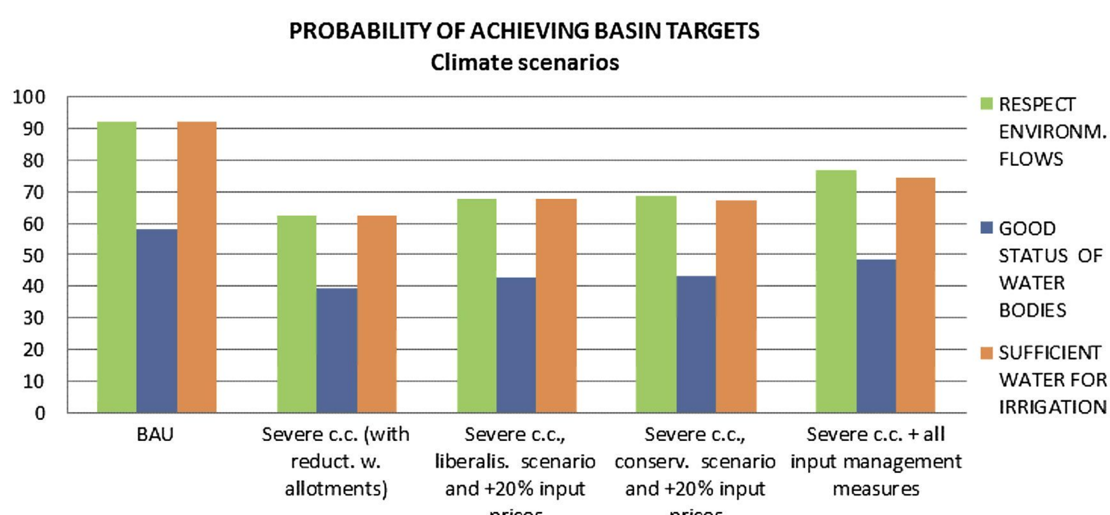

Fig. 11. Probability of meeting the basin targets for a severe climate change scenario combined with different market scenarios.

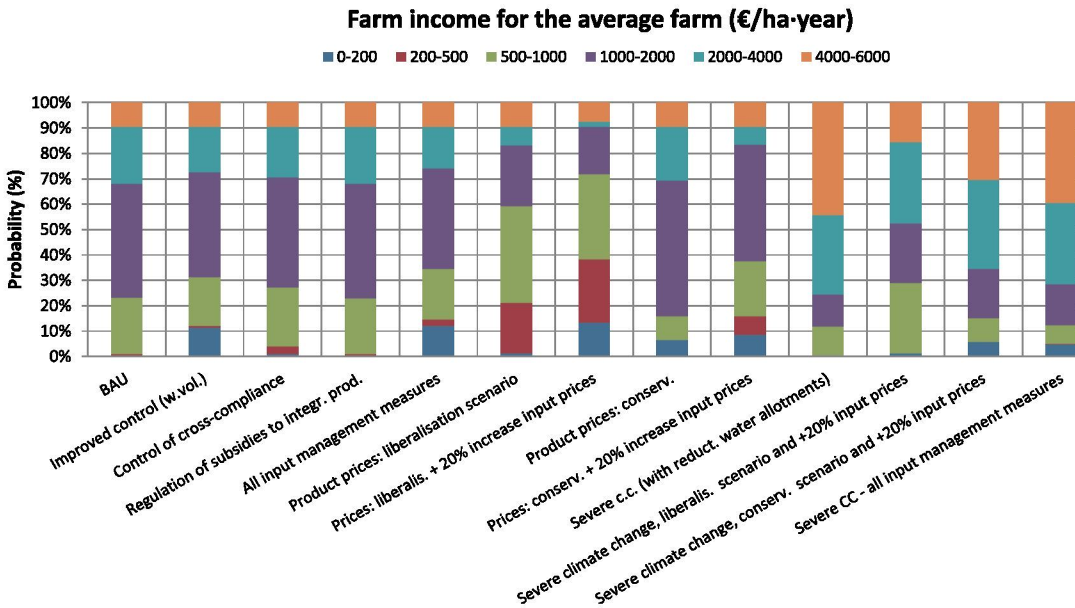

Fig. 12. Farm income of an average farm for different management, climate and market scenarios.

combination with other models. In our research, we have succeeded in developing a truly participatory integrated assessment modelling approach in which stakeholder participation and model integration are the foundations of a tool aimed at supporting decision making in the complex field of water management. The methodology presented here is a step forward from that applied in the upper Guadiana sub-basin (Carmona et al., 2011b), in which a participatory BN was used in combination with an economic model. In the current research, we have added a crop model. This allows including climate change scenario simulations, whose impacts on crops couldn't be captured by the other models. Such impacts on crops are essential in the calculation of water use and on farm income; therefore they will affect both the socio-economic and the environmental impact assessment of climate change scenarios. The result of the modelling process is an integrated tool that represents all scales involved in the water management problem and reproduces all stages in the process of water management decision making:

- The crop model represents the smallest scale in the water system, simulating the relationship between the natural system (crops) and water resources.
- The economic model represents the socio-economic system and reproduces water use decision making at the farm scale: what crops and techniques farmers decide to employ given their environmental and policy constraints.
- The BN integrates information from other models plus any relevant knowledge related to the water system at the sub-basin scale. It allows the simulation of water management decisions at the sub-basin level, that is, decisions taken by water managers.

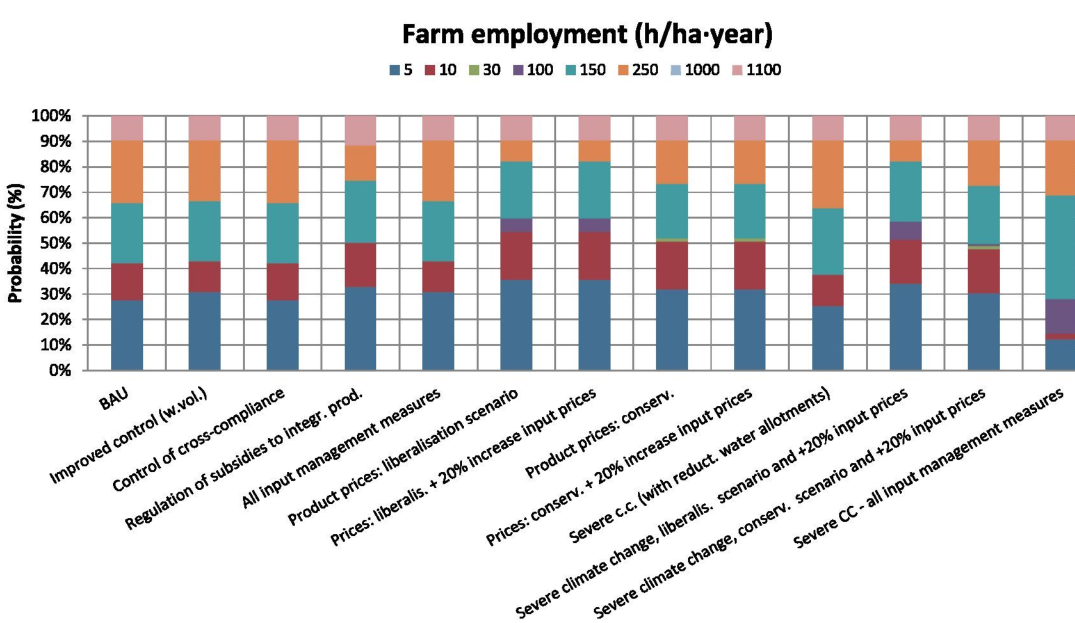

Fig. 13. Total agricultural employment in the sub-basin for different management, climate and market scenarios.

Thanks to this combination of models, the whole chain of water related decisions can be tracked and simulated, and the impacts of such decisions can be assessed at all relevant scales.

Compared to other modelling frameworks composed of purely deterministic models (Wei et al., 2009), BNs offer increased flexibility to include all types of variables and data, and the valuable opportunity to reflect uncertainty through probabilities. In addition, their participatory design improved the quality of the modelling results, thanks to a feedback process in which researchers and stakeholders shared information and views during the models' development. This mutual learning process has already been identified by other authors as one of the main benefits of participatory modelling (Hisschemöller et al., 2001; Sandker et al., 2010).

However, it should be noted that the integrated model has some limitations which should be taken into account; these limitations relate mainly to the representation of time. The difficulty of BNs to include feedback loops makes the representation of time varying processes difficult (Jensen and Nielsen, 2007; Uusitalo, 2007). As a result BNs commonly represent a period of one year; this also means that models linked to it need to operate at the same temporal scale. Comparison of current and future scenarios has been done by comparing two "snapshots", comparing current conditions with future scenarios. However, the annual scale means that there are some limitations for the economic model when dealing with long-term investments and the treatment of perennial crops. Given the annual time frame of our economic model, the surface of perennial crops has been considered constant. This is a reasonable approximation in an annual analysis of farm decisions, but becomes a limitation when dealing with long term scenarios.

Despite these limitations we should not forget that models are always representations of the real world, necessarily involving assumptions and simplifications which make the modelling feasible but which have to be considered in the interpretation of results. Notwithstanding such simplifications, the methodology developed in this research has a number of advantages compared to other tools used in integrated assessment modelling: it provides a platform for participation, something that is considered essential for modern management, while maintaining the capacity to provide quantitative output in the assessment of feasible scenarios and management options. An additional advantage of the model is the capacity to represent the different scales of the water system and the different stages in water management decision making, which allows a complete, integrated assessment of the water system.

6. Conclusions

From this research, we can draw a set of conclusions, some related to the results of scenario simulations and some related to the methodology:

(a) Results from crop simulations under climate change scenarios indicate that crop water needs would increase for all irrigated crops under both a moderate and severe climate change scenarios. At the same time crops grown without water restrictions would also increase their yields because of three factors: the effects of the increase of CO_2 concentration, growth stimulation via increased temperature and ET, and the increase of water use efficiency.

(b) The economic model gives some indication of the effects of selected scenarios in terms of cropping patterns and farm income. Comparing income for the different farm types, we can see that economic results are lower for smallest farms, belonging to the oldest irrigation communities, in all scenarios. A large size and the cultivation of tree crops seem to be a requirement for high income. Only the economic results for old farms are negatively affected by an increased compliance with the current water limitations. Regarding market scenarios, liberalisation would entail a decrease in farm income, while the conservative scenario does not seem to have such negative impacts. Finally, climate change scenarios can cause a decrease in the area of water intensive crops (maize and rice) in favour of other crops such as potato and broccoli, which are less water intensive but which require more labour. Results also show that climate change scenarios bring about an increase in farm income, due to the increase of yields in those scenarios.

(c) Results of simulations with the integrated BN have allowed the impacts of the scenarios for the whole sub-basin to be assessed. The output obtained indicates that the probability of maintaining a good status for water bodies remains lower than for the other basin objectives in all scenarios. This implies that alternative measures should be investigated or, as suggested by stakeholders, that the pollution problem is complex and that some of the factors are not directly involved with irrigation and, therefore, not represented in our models. Under a severe climate change scenario, these probabilities become 20% lower than in the current situation, even when irrigation water allotments are reduced by 33%. If this future climate scenario should occur, managers will have to look for other solutions, such as an additional decrease of water allotments or an investment in management measures which can help save water. With respect to regional employment, the results show that scenarios with the lowest availability and use of water have the highest employment figures. Water resources are exchanged for labour resources when the first become scarce.

(d) The methodology developed in this research has permitted the combination of integrated modelling and participatory approaches to address environmental assessment. BNs have proved to be useful as a participation platform and as an integrative framework where different modelling tools can be combined. It has also the property to show the uncertainty in the outcomes obtained for the selected indicators in the scenarios simulated, providing the probabilities to obtain different values for each of those indicators. Uncertainty is very relevant for water planning, which should consider the possible situations that could be faced in the future scenarios when new management strategies are designed.

The objective of our research was to obtain a tool to support decision making in water management. Such a tool needs to be able to address the complexities and uncertainties of complex environmental problems. The joint use of BNs, economic models and crop models has allowed us to simultaneously to address: (a) the different scales of the water system, (b) representation of the different stages in decision making process and (c) to explicitly express complexity and uncertainty in the system. This makes the methodology particularly relevant to the problems of decision making support in water management. The adequacy of the tool for water management support was especially highlighted by the river basin authority officials during the stakeholder meetings, who showed their interest in potentially using the model to support the development of the river new basin management plan. However, the limitations of this type of models for their practical implementation are usually a lack of continuation in time when the research is linked to limited funds. This was the case in the current research, where models were developed but there were not resources for a follow up. For a really effective support of decision making, the models should be updated and their performance monitored regularly, always with the involvement of key stakeholders.

Acknowledgements

The authors would like to acknowledge the European Commission, which funded this research through the SCENES project ("Water Scenarios for Europe and for the Neighbouring States"), from the EC PF6, n° 036822, and the MEDIATION project ("Methodology for Effective Decision-making on Impacts and AdaptaTION"), from the FP7, n° 244012. Special acknowledgement is also due to researchers from 'La Orden' experimental field, belonging to the Regional Government of Extremadura, and to the Spanish Environmental Agency (AEMET) for the data they kindly provided for this research. The authors are also grateful to Dr. Pasquale Steduto, from the FAO Land and Water Division, for the support provided in the crop modelling training.

Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.envsoft.2013.09.007.

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